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# MEASUREMENT OF KINETIC ENERGY OF VOLCANIC MICRO-TREMORS

By

Tatsuhiko WADA, Kosuke KAMO and Yasuaki SUDO

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**Abstract**

An apparatus is prepared for the purpose of direct measurement of oscillatory energy. This digital energy accumulator, called DEA-1, enables us to obtain precise results more easily than hitherto. From its application to the measurement of micro-tremors at the Volcano Aso, it is concluded that the release of energy in the form of micro-tremors is about $10^{12}$ ergs per day in the quiescent state. In addition, the variation in period of micro-tremors in relation to changes in volcanic activity can be detected by the use of DEA-1.

## 1. Introduction

From the observation of volcanic micro-tremors at the Volcano Aso, Sassa (1935, 1936) pointed out that the occurrence of volcanic micro-tremors is closely related to the activity of the volcano, and moreover suggested the possibility of forecasting volcanic eruptions by observing the micro-tremors. Following his original work, the study of micro-tremors at the Volcano Aso has been continued, and the results are satisfactory. In the light of the recently developed view of the energy process of volcanic activity, however, more quantitative techniques should be developed. In normal routine work, generally speaking, the practical treatment of a seismogram is based on simple direct reading and sampling, with some time-duration of records in the case of micro-tremors. In the case of the Aso Volcanological Laboratory, the sampling rate is about thirty minutes per day, that is, two minutes per hour. Thus, when micro-termors occur irregularly, the results obtained cannot always be relied on because of insufficient sampling. Of course, any sampling desired may be undertaken, but in general this method is impossible without complicated and troublesome work. Therefore, an apparatus which can register the energy of oscillatory motion is necessary for the purpose of direct estimation of the energy process. An apparatus for this purpose, described in the present paper and called DEA-1 for the sake of brevity, is prepared and applied practically for the observation of volcanic micro-tremors at the Volcano Aso.

## 2. Description of DEA-1

DEA-1 is composed of seven blocks of circuits as follows: rectifying, squaring, integrating, voltage-comparing, pulse-generating, counting and printing blocks. The front view and the block diagram of DEA-1 are shown in Fig. 1 and Fig. 2, respectively. Squaring means the operation of (in-put signal)$^2$. This block is prepared because of the use of the velocity type seismometer, to which nearly all seismometers of moving coil type belong. The main operation of DEA-1 is as follows. (1) The in-put signal to DEA-1 is rectified by the ultra-linear rectifier, of which the circuit is shown in Fig. 3. The operation is schematically shown in Figs. 4 (a) and (b). (2) The rectified signal is superimposed on the triangular wave, of which the level stands between $-5$ and 0 volt.

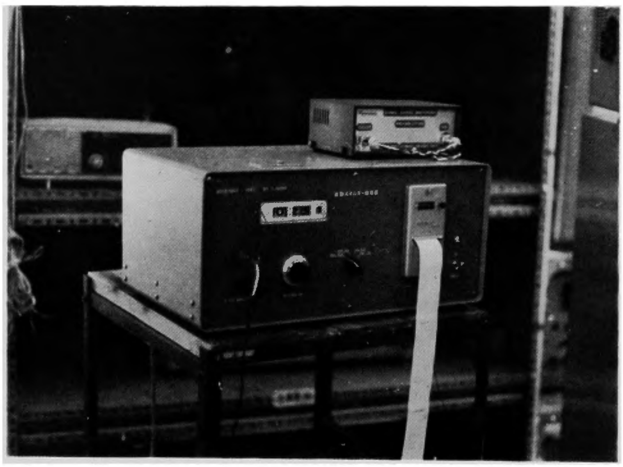

Fig. 1. Front view of DEA-1.

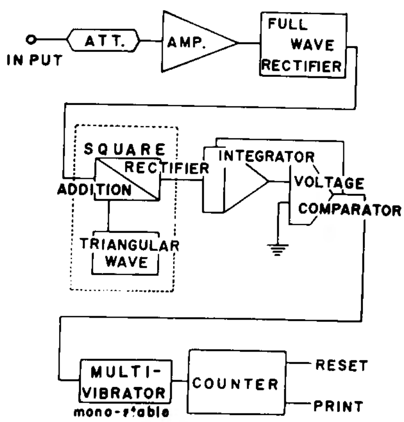


Fig. 2. Block diagram of DEA-1.

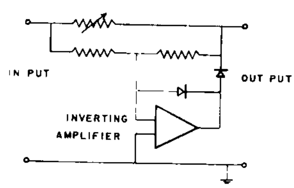


Fig. 3. Circuit of ultra linear rectifier.

The operation of modulation is shown in Figs. 4 (c) and (d), and the circuits generating triangular wave and modulation are shown in Fig. 5. (3) The modulated triangular wave is again rectified as shown in Fig. 4 (e). The area of each modulated triangular segment, of which the top is bounded by the rectified in-put signal and the lower line is the zero volt line, is proportional to the square of the in-put signal, as shown in Fig. 4 (e). Since the frequency

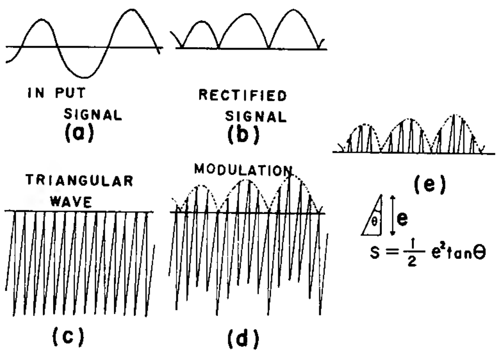


Fig. 4. Schema of squaring operation.

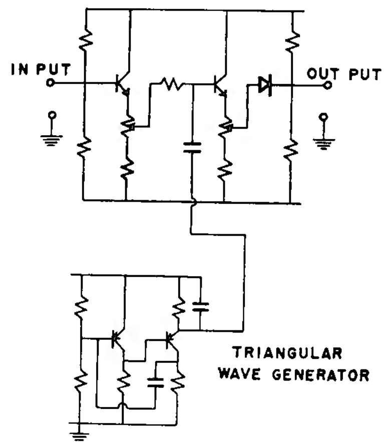


Fig. 5. Circuit of squaring part.

of the triangular wave should be determined by the upper limit of frequency of the in-put signal, which is about 10 cps in the present case, the frequency of the triangular wave is determined to be 4 kc, and then the accuracy of the squaring operation is within about $10^{-3}$ % (see also Norsworthy [1954] and Miura *et al.* [1955]). (4) The out-put of the squaring circuit is accumulated in the integrator (a condenser), and then when the charge reaches the pre-set level, a pulse is generated. The digital counter counts the pulses and the counting interval can be set at 10 minutes or 12 hours for this purpose. The circuit is shown in Fig. 6.

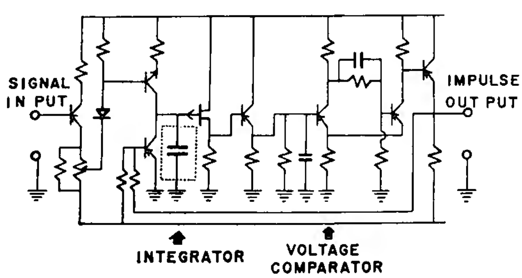


Fig. 6. Circuit of integrator and voltage comparator.

The calibration curve of the count number of DEA-1 in relation to the in-put of D. C. signal during 10 minutes is shown in Fig. 7. From this figure the response of DEA-1 may be thought to be satisfactory for the present purpose. The fluctuation of the count number due to the temperature dependency of the pulse generator is also rigorously examined, and is proved to be within 5% by attaching a suitable thermo-controller.

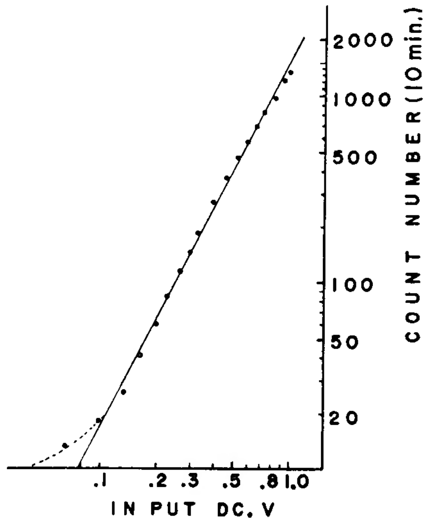


Fig. 7. Relation between count number for ten minutes and D. C. in-put into DEA-1.

Assuming that the in-put signal $S(t)$ to DEA-1 is a simple harmonic oscillation, the count number $N_\tau$ during a certain time interval $\tau$ is given by the previous exposition as follows,

$$N_\tau = \frac{1}{e_0}\int_0^\tau S^2(t)dt, \tag{1}$$

where $e_0$ is the instrumental constant of DEA-1 and is determined to be about 0.4 from Fig. 7. In the case of a perfect elastic medium, the kinetic energy $E_\tau$, passing through a unit area during a time interval $\tau$, may be expressed in

$$E_\tau = \frac{1}{2}\rho C\int_0^\tau \left(\frac{\partial w}{\partial t}\right)^2 dt, \tag{2}$$

where $w$ expresses a component of ground displacement, $\rho$ is the density of the medium and $C$ is the velocity of propagation of the wave.

In the present case, the in-put signal to DEA-1 is given by

$$S(t) = k\frac{\partial w}{\partial t}, \tag{3}$$

where $k$ expresses the instrumental constant of the system composed of the seismometer, the amplifier and the filter.

From Eqs. (1), (2) and (3), we obtain

$$E_\tau = \frac{e_0 \rho C}{2k^2} N_\tau. \qquad (4)$$

### 3. Application to volcanic micro-tremors

To measure the kinetic energy of volcanic micro-tremors, DEA-1 was employed in observations at the Volcano Aso from August 7 to December 2, 1968. The block diagram of the observational system is shown in Fig. 8. In this system, recording on smoked paper with a galvanometer is carried out simultaneously to compare the result by DEA-1 with that by direct reading.

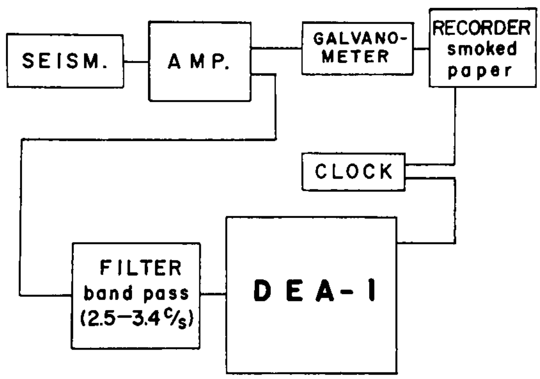


Fig. 8. Block diagram of observational system.

A vertical seismometer of moving coil type was set at Sunasenri, about 1 km south of the active crater, while the recording part and DEA-1 were in Hondo Observation Room, about 1 km west of the active crater. The characteristic constants of the instruments used are as follows: the period is 1.0 sec, the damping 1.0, and the sensitivity 2.4 volts per kine for the seismometer; and the period 0.3 sec, the damping 1.0 for the galvanometer.

In present time at the Volcano Aso, the most frequent period of micro-tremors is in the neighbourhood of 0.3 sec, and so a band pass filter (2.5~3.3 cps) of which the response curve is shown in Fig. 9 was inserted before DEA-1. The band pass filter serves to reduce the influence of earthquakes for the count number of DEA-1.

In the present observational system, the value of the instrumental constant $k$ in Eq. (3) of the previous section is determined to be $9.6\times10^3$ by considering the gains of the seismometer, the amplifier and the band pass filter. Let us

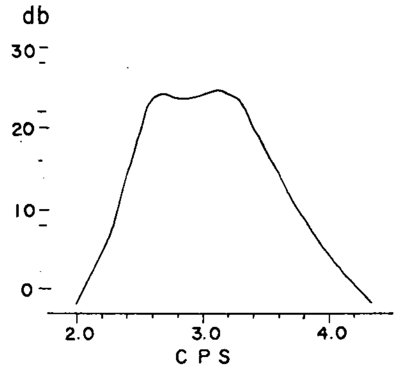


Fig. 9. Response curve of band pass filter.

$\rho=2.0$ grams per $cm^3$ for the density of the medium and $C=1.0$ km per sec for the velocity of propagation of micro-tremors (Sassa [1935] and Wada *et al.* [1965]), respectively, then the kinetic energy of micro-tremors passing through a unit area during the time interval $\tau$ is expressed as follows,

$$E_\tau=4.3\times10^{-4}N_\tau \quad \text{(ergs per cm}^2\text{)}. \tag{5}$$

## 4. Discussion

It is very interesting problem to estimate the energy release in the form of micro-tremors in comparison with the energy release of eruption, because the principal study of physical volcanology is based upon the energy process of volcanism. Assuming that the micro-tremors are propagated from the 1st crater with the velocity of 1.0 km per sec according to the evaluation of Sassa (1935) and Wada *et al.* (1965), the kinetic energy of micro-tremors passing through a

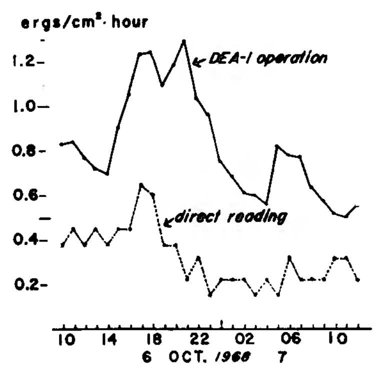


Fig. 10. Comparison between results obtained by DEA-1 (solid circle) and those by direct reading (open circle) for each period of one hour from 6 to 7 October, 1968.

unit area is about 20 ergs per day. Considering that the distance between the observation point and the source is about 1.0 km, the total energy of micro-tremors, if the micro-tremors are bodily waves, is about $2\times10^{12}$ ergs per day (If surface waves, about $2\times10^{7}$ ergs per day). In comparison with the energy of eruption, which is estimated to have been $10^{16\sim18}$ ergs at the Volcano Aso in 1958 and 1965, though the energy release in the form of micro-tremors forms only small part, the occurrence of micro-tremors bears a close relation to volcanic activity as characterized by the eruptions. This fact seems significant in relation to the problem of forecasting eruptions.

Results obtained both by DEA-1 and by direct reading are shown in Fig. 10, which represents the energy passed through a unit area for an hour during October 6~7, in 1968, and in Fig. 11, which represents the energy passed through a unit area for a day during September~October, in 1968. In general, the results obtained by DEA-1 are larger than by direct reading. This is due to the following reason. In DEA-1 operation, the energy evaluation is based on the equation $\int\left(\frac{\partial w}{\partial t}\right)^2 dt$. On the other hand in direct reading, the evaluation is based on the equation $\int\left(\overline{\frac{\partial w}{\partial t}}\right)^2 dt$, when $\left(\overline{\frac{\partial w}{\partial t}}\right)$ means a mean velocity in the duration of sampling. And also the insufficient sampling undertaken entails a failure to record some intermittent occurrences of micro-tremors. Conversely, when

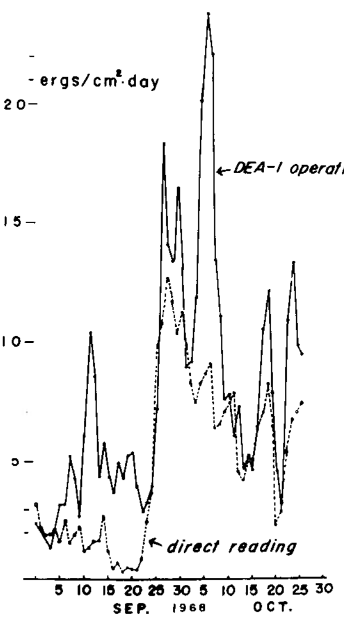


Fig. 11. Comparison between results obtained by DEA-1 (solid circle) and those by direct reading (open circle) for each period of twenty-four hour from September 1 to October 30, 1968.

several local earthquakes, some perceptible, are recorded, for example, on September 11~12 and October 4~6 as represented by Fig. 11, their influence causes an overestimation on the results by DEA-1 in comparison with results by direct reading. The defect must be noticed, but it is not fatal because it can be corrected easily. In general, the operation of DEA-1 is thought to be preferable to the method employed until now. An example of a seismogram used for energy estimation is shown in Fig. 12, and corresponds to a portion of the results in Fig. 10.

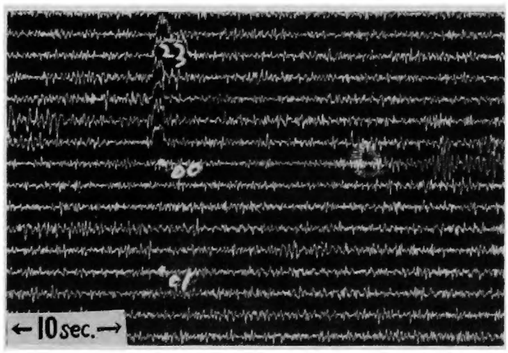


Fig. 12. An example of a seismogram on which the kinetic energy by direct reading is read in Fig. 10.

Another application of DEA-1 for micro-tremors is concerned with the variation of period of micro-tremors in relation to the change of volcanic activity as suggested by Sassa (1936) and Kamo (1960). To examine this phenomenon

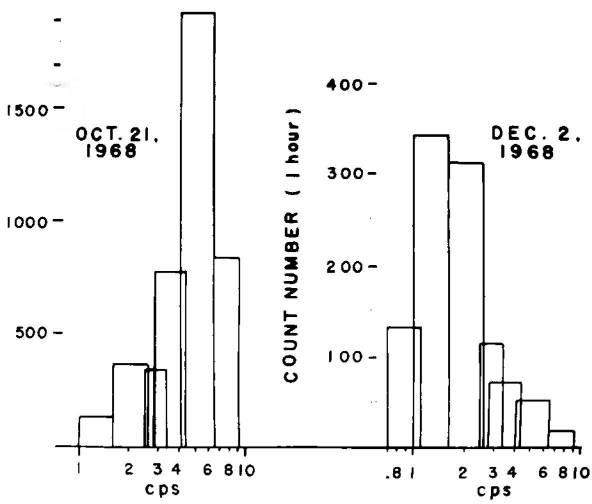


Fig. 13. Power spectra for volcanic micro-tremors.

by the application of DEA-1, the micro-tremors are recorded on magnetic tapes and the playback signal is accumulated by DEA-1 through seven band pass filters, of which the frequency ranges are 0.7~1.1, 1.0~1.6, 1.6~2.6, 2.5~3.4, 2.8~4.4, 4.1~6.5 and 6.6~9.1 cps, respectively. An example of an active case is that of October 21, 1968, when a large pool of muddy and boiling water was seen at the bottom of the crater, and continuously trained micro-tremors occurred with larger amplitude. On the other hand, an example of a comparatively inactive case is that of December 2, 1968, when the bottom of the crater had been dried up at red heat, the amplitude of micro-tremors became smaller, and their occurrence was slight. As seen in Fig. 13, the spectra are clearly different in the two cases. On October 21 the peak is at about 5 cps, and on December 2 the peak is at about 1.5 cps.

## 5. Summary

When the volcanic energy process is studied, it is necessary to estimate precisely the kinetic energy of the volcanic micro-tremors. For this purpose, a digital accumulator which is able to measure continuously and automatically the kinetic energy of the volcanic micro-tremors is prepared.

Observing the volcanic micro-tremors accompanied by the recent quiescent activity of the Volcano Aso by the use of DEA-1, we obtained the following results:

(1) DEA-1 is able to express continuously the state of volcanic activity as a variation of the kinetic energy of micro-tremors.

(2) The variation is practically identical with that obtained by the direct reading method on a seismogram. In the case of irregular occurrence of micro-tremors, however, the use of DEA-1 is clearly preferable to direct reading with sampling.

(3) On the assumption that the micro-tremors were bodily waves having a velocity of propagation of 1 km per sec, the kinetic energy released in the form of micro-tremors from the Volcano Aso amounts to about $2\times10^{12}$ ergs per day.

(4) The value of $10^{12}$ ergs per day seems unexpectedly small in comparison with the kinetic energy of an eruption, namely about $10^{16\sim18}$ ergs.

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